Multi-Sensor Systems: Multiplicity helps

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Abstract

Today many tracking and surveillance systems show multi sensor configurations, which are used to enhance the breadth of measurement and likewise to increase the capability of the system to survive if any individual sensor fails. Currently, multi sensor systems rely on a central processor where global data fusion takes place, or a central communication medium through which all messages between sensors must be transferred. Such centralized architectures give rise to problems with communication and computational bottlenecks and are susceptible to total system failure if the central facility should fail. Beside the high reliability of a distributed multi sensor system it enables a new possibilities of signal processing for enhancing target detection.

The objective of this article is to introduce multi sensor surveillance systems to understand the basics of these networks, to stimulate new concepts, theories, and applications in this area, and to give a background to the following lectures in the NATO SET-157 Lecture Series: *Multisensor Fusion: Advanced Methodologies and Applications*.

The starting point for introducing multi sensor systems is given by looking closer into distributed radar network consisting of several transmitters and receiver units spread over an

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area.

1 Introduction

Multi sensor networks are a promising technology that is attracting more and more researchers and practitioners alike. Using sensors which are not affected by weather conditions, time-of-day, or temperature, like radar or sonar systems, enables to keep an area under surveillance continuously. Multi sensor systems are characterized by utilizing various sensors to detect targets, classify and track them. Designing a distributed network using only a single type of sensor, for instance radar or sonar, offers a new paradigm for signal processing. Such an optimal multiple-input multiple-output (MIMO) radar network is characterized by using multiple transmitters which simultaneously transmit diverse waveforms, which are orthogonal coded in the optimal case, and by utilizing multiple receivers to receive all reflected signals. These networks offer the potential of enhancing resolution, improving interference and jamming suppression, and fading migration. Furthermore, a single type sensor network can significantly improve target detection, parameter estimation, as well as target tracking and recognition performance.

Radar research is not a young research discipline. Christian Hülsmeyer was the first who used radio waves to detect *the presence of distant metallic objects*, in 1904. He received Reichspatent Nr. 165546 [1] for his pre-radar device, which he called *telemobiloscope*, in April 1904. He demonstrated the feasibility of detecting the presence of a ship in dense fog from the Hohenzollern bridge in Cologne, and later patent 169154 [2] for a related amendment for ranging. Before and during the Second World War, developments by the British, the Germans, the French, the Soviets and the Americans led to the modern version of radar. The radar capabilities and usefulness were dramatically improved during the war. Robert Watson-Watt demonstrated the capabilities of a working prototype to the British Air Ministry in January 1935 [3]. It served as the basis for the Chain Home air defence radar, the first radar network consisting of separated transmit and receive antennas, which were separated by a few hundred meters. In these early days of radar history systems could easily be jammed. To overcome this problem German radar engineers developed a system called *Klein-Heidelberg Parasit*, making use of transmissions from the Chain Home coastal early warning stations as a radar illumination source. The direct signal from the Chain Home transmitter to the *Klein-Heidelberg* receiver served as a primary signal. The reflected signal from the aircraft was the second signal. Due to the longer path of the reflected signal compared to the direct signal the weaker echo signal possesses a time delay. From geometry the target is

located on an ellipse with the transmitter and receiver antennas being in the focal points of the ellipse. To determine the bearing angle of the echo the Germans used a direction finding antenna. With the knowledge of bearing angle and time delay they knew the position of the aircraft on the ellipse. This system gave the Germans a radar with a range of up to 400 km and an accuracy in range of 1 to 2 km and in bearing of about 1 degree [4]. This scheme benefited from several advantages: firstly it was completely covert and secondly it was very difficult to jam, since conventional jamming would also have affected the operation of the Chain Home network [6]. With *Klein-Heidelberg* the first operational bistatic radar system was established. Over the years three resurgences at bi- and multistatic radar occurred. The first in the 1950s and the second in the late 1960s, when data link transmitters on satellite and ground-based receivers were used to investigate planetary surfaces. In the early 1990s the third resurgence in bi- and multistatic radar systems started, which included a great deal of interest in Passive Coherent Location (PCL) systems which use illuminators of opportunity, like radio, TV, or mobile-stations.

Progress in technology has opened new features in radar systems, like in the 1960s the phased-array antennas, allowing radars to instantly change search direction from pulse-to-pulse. Furthermore computer capabilities have increased dramatically, which allows applying digital signal processing to radar processing, e.g. for adaptive array processing. Over the last decade the progress in signal processing and wireless communication technology, where data throughput and link range was improved, allowed radar designers to consider distributed sensor networks based on Multi-Input Multi-Output (MIMO) techniques. [7]-[9]

MIMO radar systems illuminating the surveillance area simultaneously or in a time-multiplexed way with orthogonal waveforms from different locations and receiving the reflected electromagnetic wave at spatially separated receivers, possess significant potential for [10]:

- fading migration,
- higher resolution for collocated transmit and receive antenna,
- interference and jamming suppression,
- improved target detection, location, recognition, and tracking,
- higher sensitivity to detect slowly moving targets,
- possible widely separated transmit/receive antenna,
- better parameter identifiability due to joint estimation,
- orthogonal waveforms increases information in the same bandwidth,
- increased signal-to-noise ratio (SNR),
- increased electronic protective measures (EPM) capabilities.

Fig. 1 shows a distributed multiple-input multiple-output radar network. All nodes are transmitting orthogonal waveforms and receive the echoes simultaneously. All receivers perform

a pre-processing and transmit their results to a central processing system for data fusion.

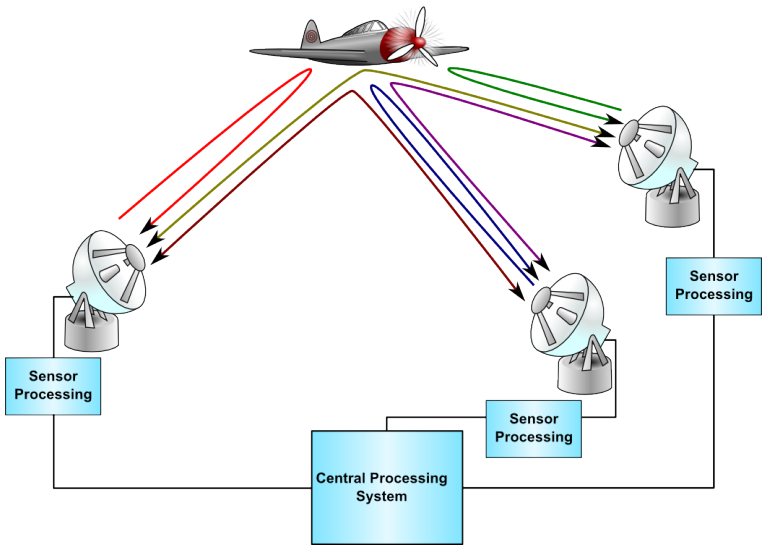

Figure 1: A distributed multiple-input multiple-output radar network

2 Multi Radar Network Configuration

Many of the particular problems of a multi radar network configuration are a consequence of the bistatic geometry where the separated transmitter and receiver introduce various modifications. In detail the bistatic geometry was analyzed by Jackson [5].

2.1 Multistatic Geometry

In a bistatic configuration the transmitter (TX) and receiver (RX) pair are generally separated by a distance called baseline (normally denoted by L). A MIMO radar is nothing else than a composition of a set of N bistatic TX-RX pairs. Each transmitter-receiver pair defines a bistatic plane with the target. Hence, each new target defines a new bistatic plane. A monostatic radar determines target range directly from the measurement of the signal travelling time τ from the transmitter to the target and back to the receiver. In the bistatic case the signal path it the sum $R = R_t + R_r$. R_t and R_r are now the range from target to TX and RX, respectively. In general $R_t \neq R_r$. To estimate R from τ the receiver must know the exact transmission time t_0, which means that the Tx-Rx pair must be synchronized in time. Furthermore the receiver must know transmitter location with respect to his own.

A characteristic measure that describes the bistatic geometry is the bistatic angle β that is the angle between vectors from the target to TX and RX, which defines the target's position on the isorange contour, as described in Fig. 2.

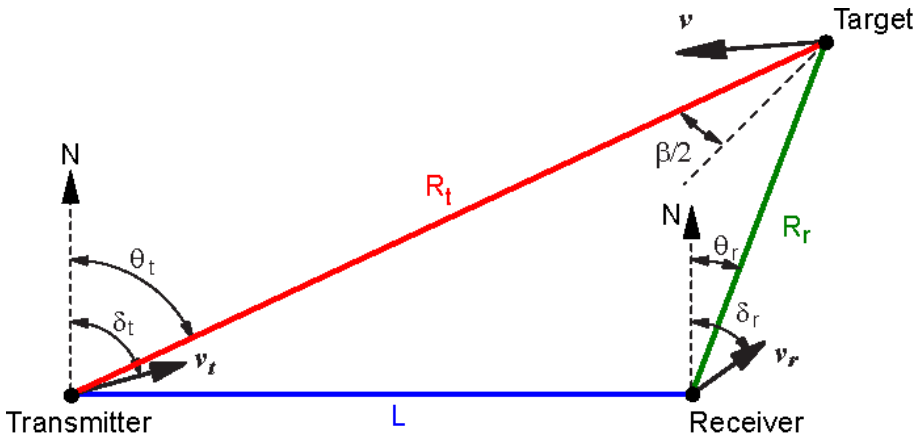

Figure 2: Bistatic geometry and notification

2.2 Radar Equation for multistatic Radar

The multistatic radar equation is derived in a similar way to that for a monostatic radar. By the nature of a multistatic radar system, the potential SNR gains from all involved transmit/receive-pairs by MN, where N is the number of transmitters and M is the number of receivers. In the simplest form this is:

$$SNR = \sum_{i=1}^{N} \sum_{n=1}^{M} \frac{P_t\, G_{tx}(i)\, G_{rx}(n) \sigma_b\, \lambda^2}{(4\pi)^3\, k\, T_0\, B\, F\, R_{tx}^2(i) R_{rx}^2(n)\, L} \tag{1}$$

where P_t is the transmit power, λ is the radar wavelength, $G_{tx}(i)$ is the gain of the transmit antenna i, $G_{rx}(n)$ is the gain of the receive antenna n, σ_b is the bistatic radar cross-section of the target, F is the receiver noise figure, R_{tx} is the transmitter-to-target range, R_{rx} is the target-to-receiver range, k is the Boltzmann's constant, T_0 is 290 K, B is the signal bandwidth, and L is the transmission loss. Each transmits-receive pair contributes to the overall system SNR, resulting in the MN gain if all sensors are synchronized and coherent signal processing takes place. In the non-coherent case the gain of the multi radar network is only N.

Contours of constant SNR are loci corresponding to $R_{tx}(i)\, R_{rx}(n)$ = constant, which follow the lines of *ovals of Cassini* [5]. For monostatic radars the contours of constant signal-to-noise ratio are circles, as shown in Fig. 3.

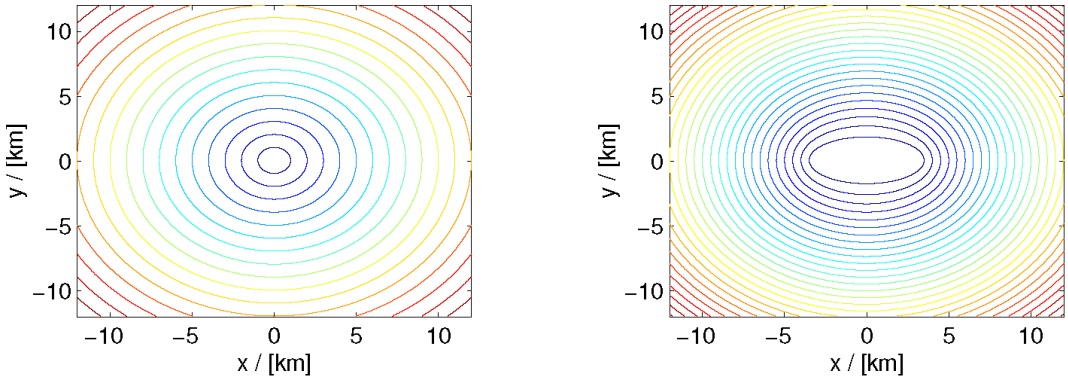

Figure 3: Comparison between monostatic (left) and bistatic constant SNR. Baseline is 6 km in the bistatic case.

2.3 Multistatic Doppler

Doppler shift depends on the motion of the target, transmitter, and receiver (see Fig. 2). In general the equation can be quite complicated, as the time rate of change of the total path

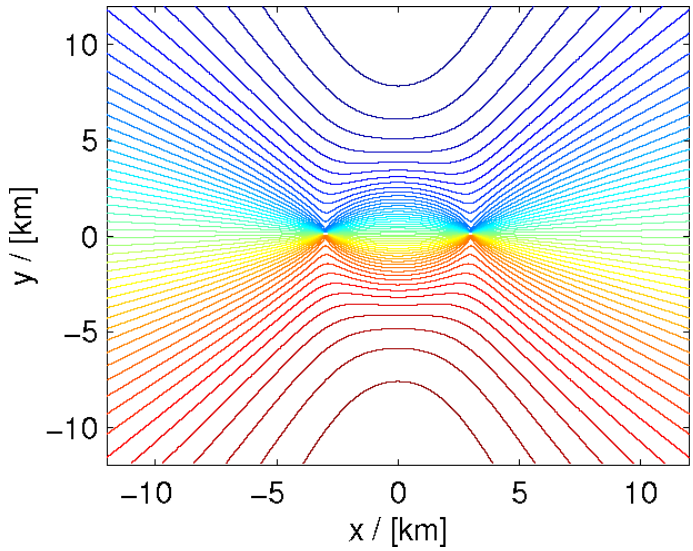

Figure 4: Bistatic isodoppler contours

length from transmitter-target-receiver has to be taken into account [11]:

$$f_D = \frac{1}{\lambda}\left[\frac{\partial}{\partial t}(R_t + R_r)\right] = \frac{1}{\lambda}\left[\frac{\partial R_t}{\partial t} + \frac{\partial R_r}{\partial t}\right] \tag{2}$$

In the easy case when only the target is moving the Doppler shift f_D can be determined by:

$$f_D = \frac{2\,v}{\lambda}\cos(\delta)\,\cos(\beta/2) \tag{3}$$

where v is the velocity of the target, λ is the radar wavelength, δ is the angle of the target velocity with respect to the bisector of the transmitter-target-receiver angle, and β is the bistatic angle. Contours of zero Doppler are ellipses of constant bistatic range. Contours of maximum Doppler are hyperbolae crossing the ellipses orthogonally [5]. Some special cases of Eqn. (3) are shown in table 1. A moving target will not present zero Doppler to all

Table 1: Geometry dependent forms for Doppler shift of Eqn. (3)

δ	β	f_D	condition (geometry)
—	$0°$	$(2v/\lambda)\ \cos\delta$	monostatic
$0°$	$0°$	$(2v/\lambda)$	monostatic
$0°$	—	0	forward scatter
$\pm 90°$	—	0	$v \perp$ to bisector
$\pm\beta/2$	—	0	v points to tx or rx
$0°,\ 180°$	—	$\pm(2v/\lambda)\ \cos(\beta/2)$	$v \Rightarrow$ bisector
$90° \pm \beta/2$	—	$\mp(v/\lambda)\ \sin(\beta)$	$v \perp$ to tx or rx LOS

receiving sites simultaneously but only to two receivers in a radar network. This can usefully be exploited in multistatic radar systems.

2.4 Target Cross Section

The radar cross section (RCS) of a target σ_B in a bistatic scenario has been studied extensively in [13]. As the measurement of bistatic RCS is a function of aspect angle and bistatic angle the setup is more complex than for measuring the monostatic RCS.

It has been identified that three phenomena contribute to the bistatic RCS: (*i*) resonance scatter, (*ii*) forward scatter, and (*iii*) specular reflection. For the monostatic RCS resonance scatter and specular reflection apply, while the forward scatter appearance only in the bistatic case.

A way to describe the resonance scatter effect is by the interference between the incident wave and the creeping wave, which circles the target and either adds to or subtracts from the total field on the leading conductive surface. For instance, a conducting sphere of radius a shows resonances in the region $0.5 < 2\pi a/\lambda < 10$. If the wavelengths are in the order of discrete object dimensions, for example fuselage, wings, tail of an aircraft, the net result of the resonance can significantly enhance RCS, when compared to the optical region, which

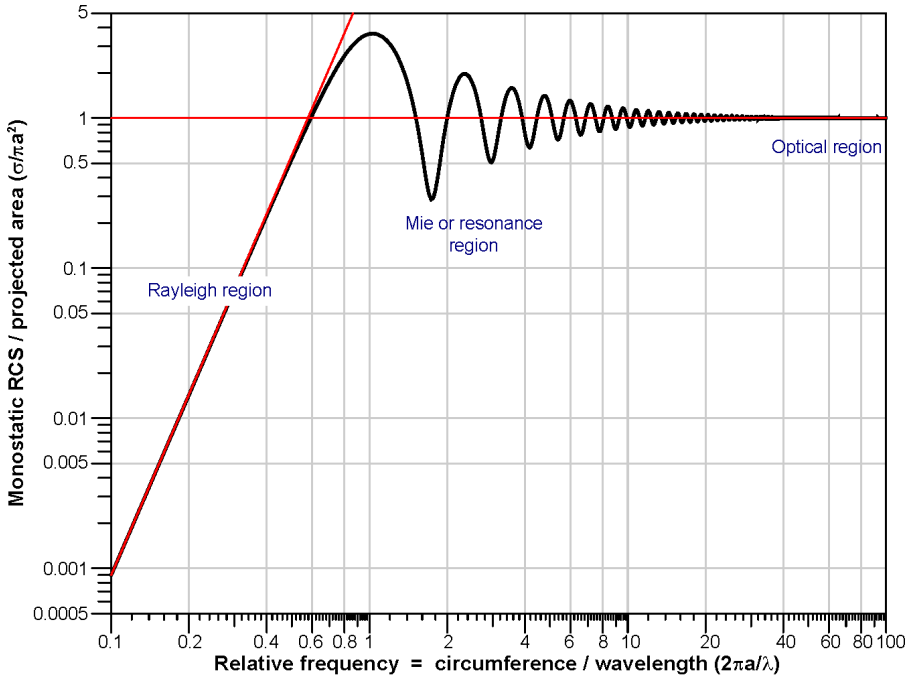

Figure 5: Monostatic radar cross section [RCS] of a perfectly conducting metal sphere as a function of frequency (computed by Mie theory)

for the sphere starts at $2\pi a/\lambda > 10$. Fig. 5 illustrates these effects for an perfectly conducting metal sphere [14].

If the target is near the transmit-receive baseline, the forward scatter effect dominates (see Fig. 6). While range information of the target cannot be obtained, due to the same time-delay of the direct and reflected signal, the forward scatter effect gives rise to a substantial enhancement in RCS, even for stealthy targets. An easy explanation can be given using Babinet's principle, which describes that a perfectly absorbing target will generate the same forward scatter as a target shaped hole in a perfectly conducting screen. The forward scatter RCS is approximately $\sigma_B = 4\pi A^2/\lambda^2$, where A is the target projected area, and the angular width θ_B of the scattering will be in the order of λ/d radians, where d is the target linear dimension.

Fig. 7 shows how these vary with frequency, for a target of the size of a typical aircraft, and shows that frequencies around VHF and UHF are likely to be optimum for exploiting forward scatter [6].

The third phenomenon in bistatic RCS is specular reflection, which occurs by tilted surfaces or facets on stealth platforms that have purposely been designed to be directed away from expected monostatic radar locations. By choosing the locations of the bistatic stations care-

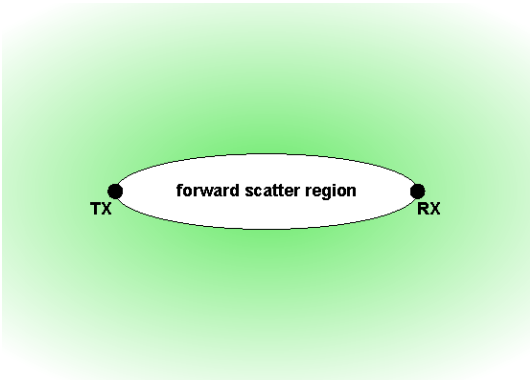

Figure 6: Illustration of forward scatter geometry

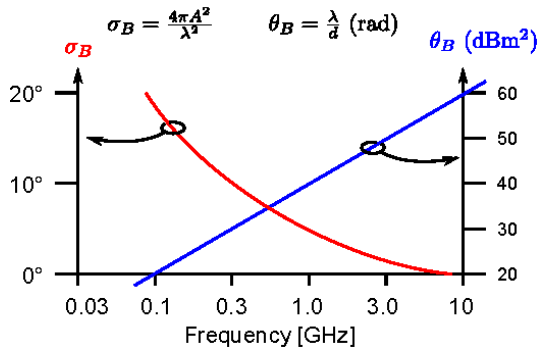

Figure 7: Forward scatter RCS $4\sigma_B$ and angular width θ_B of scatter for a typical small aircraft target ($A = 10\,\mathrm{m}^2$, $d = 10\,\mathrm{m}$) [12]

fully these off-normal speculars of large amplitude can be detected and tracked or networked together to support some level of engagement. As well chosen bi- and multistatic geometries are required and the received flashes will be of short duration, it seems very optimistic to ascribe more than a fence-type alerting and coarse indication capability when exploiting specular reflections from stealth aircraft.

3 Types of multistatic radar networks

The interest of system designers in multistatic radar networks is seen in their enormous potential. Beside relatively simple designs, such as the case with a single illuminator and two receivers, extremely complex geometries can be constructed, with high demand on communication, processing and complex algorithms.

Examining the transmitter and receiver operation, a multistatic network can be divided into three principle categories of operation:

1. monostatic operation,
2. bistatic operation, and
3. any combination of the first two categories.

In the monostatic case, each radar transmits a specific waveform and receives and evaluates only the echo generated by this signal. In a multistatic radar network a minimum of one

illuminator and N spatially separated receivers observe a common area. Each transmitter-receiver pair is in fact a bistatic radar. In the general case each node in the network acts as a transmitter and as a receiver and represents a fully MIMO radar system. In this case, the receiver accepts echoes from all reflected signals. Fig. 8 shows a schematic illustration of these different topologies.

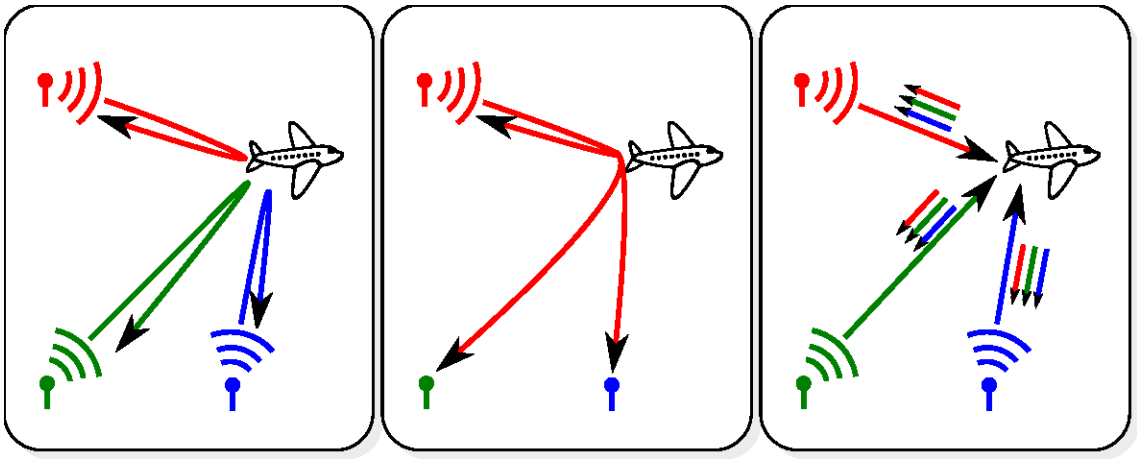

Figure 8: Modes of operation: The multiple monostatic case, the multiple bistatic case and the fully multistatic case. The colored lines indicate the different waveforms used in each of the cases.

A further categorisation is applicable, namely if a node in the multistatic network is *active*, which means it is transmitting a dedicated signal, or *passive*. In the passive mode the receiver exploits illuminators of opportunity such as TV or radio broadcasts. Combining active and passive modes enhances covert operation of the multistatic network. For locating jammer sources passive operation in a network can be very useful. Jammers can be located with a multistatic radar network, based on advanced cross correlation signal processing techniques, to provide their location through the time difference of the received jammer waveform at each receiver [17].

A fundamental issue for multistatic sensor network is coherency, as information extraction and processing potential (e.g. imaging etc.) is enhanced significantly compared to non-coherent systems. In multistatic networks we must consider the spatial coherence in addition to the temporal coherence. The spatial coherence is defined as the ability to maintain phase stability of the RF signals and interference between separated stations [11]. Hence, the classification of multistatic radar systems can likewise be grouped into the following three categories:

1. Coherent networks,
2. Short term coherent networks, and
3. Incoherent networks.

In the first category each transmitter-receiver pair knows accurately the introduced phase-shift and can maintain it for a long period of time, for instance to determine the Doppler shift induced by the moving target or to perform signal processing in a synthetic aperture formation. To obtain increased target information from the scattered electromagnetic field (phase and amplitude) more complicated and demanding system concepts are required.

The concept is similar to a sparsely populated phased array antenna. The sparsity may result in grating-lobes. In order to avoid this effect and have adequate sampling of the spatial frequencies, either more nodes must be added to the network or location strategies that avoid harmful grating lobes have to be computed. This makes the system ever more complex and potentially expensive [15].

In a multistatic radar network of the second category, phase stability can only be maintained for a relatively short period. It permits joint signal processing so all information contained in the reflected signal can be extracted, and allows to plot and track using different receivers. The target position cannot be determined by phase, as achieved by the first network type, but it can be estimated through Difference in Time of Arrival (TDOA) [16].

In an incoherent network a lot of power and available information from the target signal is unusable. The reason is that only the signal envelope can be used for extracting information while the phase information is useless. This is harmful for specific signal processing tasks, for instance joint coherent signal processing for mainlobe jamming cancellation.

In comparison between these categories, incoherent networks are the simplest to fabricate but have the disadvantages of the lowest sensitivity, least flexibility and highest information loss. Complexity and cost rise with the demand on coherence in the multistatic network.

4 Examples of multistatic radar systems

Examples of multistatic radar systems can be broken up into two main categories: (*i*) defence and (*ii*) civilian. Today there is a resurgence of interest in bi-/multistatic radar networks due to the recent technology progress in high-speed signal processing, precision navigation by global navigation satellite systems (GNSS), wideband communications and digital antennas, which will replace phased-array antennas. Many experts predict that this time the experimental systems will evolve into operational systems.

Mainly multistatic radars networks deployed in defence and security applications are used to form a tailored surveillance area to significantly improve the detection of non-cooperative objects, especially stealthy targets. Many parameters of a radar network can be adapted, e.g. baseline length, carrier frequencies, transmitted signal types, and polarization for each receiver, to fulfill the specific application of interest. Hence, multistatic radar systems are widely used for ground based networks for air defence. The same concept is usable for underwater surveillance using multistatic sonar [18].

A short survey of existing multistatic radar systems is given here, which does not claim to be complete:

1. Massachusetts Institute of Technology's Netted Radar System. [19]
2. CELLDAR by Roke Manor Research Limited, UK. [20]
3. Hamburg University of Technology's Automotive Radar Network [21]
4. Jindalee Operational Radar Network [22]
5. Norwegian Defence Research Establishment's Experimental Bi-Multistatic CW Radar [23]
6. SAIC's Passive, Multi-Static Radar System [24]
7. University College London's NetRad System [25]
8. Xidian University's Coast-ship Bi/multistatic Ground-wave Over-the-horizon Radar [26]

Several passive radar systems make use of multiple spatially diverse transmitters and hence may be considered to operate multistatically.

5 Conclusion

This tutorial has attempted to provide an introduction to multistatic radar systems. Current interest in multistatic sensor networks is high as bistatic approaches may provide solutions to some current problems. Due to the technology progress over the recent years in signal processing, synchronization, wireless communications, navigation, and digital antennas practical systems can now be realized.

References

[1] C. HÜLSMEYER, "Patent DE165546: Verfahren, um metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.", 30. April 1904

[2] C. HÜLSMEYER, ”Patent DE169154: Verfahren zur Bestimmung der Entfernung von metallischen Gegenständen (Schiffen o. dgl.), deren Gegenwart durch das Verfahren nach Patent 16556 festgestellt wird.”, 11. Nov. 1904

[3] WATSON-WATT, SIR ROBERT, ”The Pulse of Radar”, Dial Press, 1959

[4] D. PRITCHARD, ”The Radar War: Germany’s Pioneering Achievement, 1904-45”, Patrick Stephens Limited, Wellingborough, England, 1989, ISBN 1-85260-246-5

[5] M.C. JACKSON, ”The geometry of bistatic radar systems,” Communications, Radar and Signal Processing, IEE Proceedings Part F , vol. 133, no. 7, pp. 604-612, December 1986

[6] H. GRIFFITH, ”Bistatic: introduction and historical background”, NATO SET-136 Lecture Series, 2009

[7] J.G. FOSCHINI, ”Layered space-time architecture for wireless communication in a fading environment when using multiple antennas”, Bell Labs Technical Journal, Vol. 1, pp. 41-59, 1996.

[8] N.B. SINHA, R. BERA, AND M. MITRA, ”Digital array mimo radar and its performance analysis”, Progress In Electromagnetics Research C, Vol. 4, pp. 25-41, 2008

[9] J.G. FOSCHINI AND M.J. GANS, ”On the limits of wireless communications in a fading environment when using multiple antennas”, Wireless Pers. Commun., Vol. 6, pp. 311-335, 1998.

[10] J. LI AND P. STOICA, ”MIMO radar signal processing”, John Wiley & Sons, Inc., Hoboken, New Jersey, 2009

[11] NICHOLAS J. WILLIS, ”Bistatic Radar”, Artech House, Boston, London, 1991

[12] EDITED BY N.J. WILLIS AND H.D. GRIFFITHS, ”Advances in Bistatic Radar”, SciTech Publishing Inc., Raleigh, NC, ISBN 1891121480, 2007

[13] J.I. GLASER, ”Bistatic RCS of complex objects near forward scatter”, IEEE Trans. Aerospace Electronic Syst., Vol. AES-21, No. 1, pp. 70 - 78, Jan. 1985

[14] M. SKOLNIK, ”Radar Handbook”, 2nd Edition, McGraw-Hill Inc., New York, 1990

[15] C. BAKER, ”An Introduction to Multistatic radar”, NATO SET-136 Lecture Series ”Multistatic Surveillance and Reconnaissance: Sensor, Signals and Data Fusion”, April 2009

[16] JIĚÍ HOFMAN, JAN BAUER, ”Tajemství radiotechnického pátrače Tamara [The Secret of Radiotechnical Sensor Tamara]”, 2003, ISBN 80-86645-02-9

[17] R.J.E. POLLARD; D.M. GOULD, ”Bistatic Sensor Cross Correlation for Emitter Location”, 28th European Microwave Conference, Oct. 1998, Vol. 1, pp.:540-545

[18] S. CORALUPPI, ”Multistatic Sonar Localization”, IEEE Journal of Oceanic Engineering, Vol. 31, Issue 4, Oct., pp. 964 - 974, 2006

[19] G.H. KNITTEL, ”Phase II Netted radar demonstration”, NASA STI/Recon Technical Report N, 81, October 1980

[20] http://www.roke.co.uk/sensing/radar.html,
http://web.archive.org/web/20060308181747/http://www.roke.co.uk/sensors/stealth/celldar.asp

[21] F. FOLSTER, H. ROHLING, ”Data association and tracking for automotive radar networks”, IEEE Transactions on Intelligent Transportation Systems, 6(4), pp. 370-377, December 2005

[22] S.B. COLEGROVE, ”Project Jindalee: From Bare Bones To Operational OTHR” IEEE International Radar Conference - Proceedings. pp. 825-830, 2000

[23] T. JOHNSEN, K.E. OLSEN, R. GUNDERSEN, ”Hovering helicopter measured by bi-/multistatic CW radar”, Radar Conference, 2003 Proceedings of the 2003 IEEE, pp. 165-170, May 2003

[24] S. CARSON, D. KILFOYLE, M. POTTER, J. VANCE, ”A Passive, Multi-Static Radar System”, Proceedings of the IET International Conference on Radar Systems, October 2007

[25] T.E. DERHAM, S. DOUGHTY, K. WOODBRIDGE, C.J. BAKER, ”Design and evaluation of a low-cost multistatic netted radar system.” Radar, Sonar & Navigation, IET, 1(5): pp. 362-368, October 2007

[26] C. BAIXIAO, C. DUOFANG, Z. SHOUHONG, Z. HAO AND L. MAOCANG ”Experimental System and Experimental Results for Coast-ship Bi/multistatic Ground-wave Over-the-horizon Radar”, International Conference on Radar 2006, CIE ’06. pp. 1-5, October 2006